

PULSE THERMAL DIFFUSIVITY MEASUREMENTS
OF SEDIMENTARY ROCKS

By

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CHAPTER I

INTRODUCTION

The thermal transport properties of sedimentary rocks are of interest to petroleum geology because of the possibility of using thermal profiles of sedimentary basins to evaluate the oil and gas generation potential of the rocks. The thermal transport properties are also important because of the current interest in the thermal methods of petroleum production from underground oil-bearing rocks and sands. At present, the thermal transport properties of petroleum reservoir-type rocks are not very well characterized, and few reliable data are available in the literature. The properties of interest are the thermal conductivity, the thermal diffusivity, and the specific heat. The relation of these properties to such other parameters as porosity, temperature, pressure, and fluid saturation is also important in developing predictive models of the thermal history of sedimentary basins and in the thermal oil-recovery processes.

Techniques for thermal conductivity measurements can be grouped into steady-state temperature and transient temperature methods. The steady-state methods require simultaneous measurements of the steady-state heat flux and temperature gradient through the test samples. The samples are usually in the form of spheres, cylinders or slabs, for which solutions to the differential equation of heat conduction are readily available. Drawbacks common to all steady-state methods are the

relatively long time needed to attain thermal equilibrium as well as the necessity of sophisticated guarding systems to minimize as much as possible the edge or end effects (since no thermal insulation is perfect in practice).

The transient methods are much faster than the steady-state methods. Some of the transient methods determine thermal conductivity directly, but most of them lead to a measurement of thermal diffusivity. The test sample is initially in a state of thermodynamic equilibrium. An addition of thermal energy to the sample induces a transitory temperature change as the sample seeks a new state of equilibrium. A measurement of the temperature as a function of time at several points in the sample leads to the determination of thermal diffusivity or thermal conductivity.

Because of the short duration of test, these methods are much faster than the steady-state methods, and also they are not restricted to measurements of the conductivity of dry samples only. This is important because of the increasing interest in materials where moisture affects the thermal conductivity, like soils.

The most commonly used techniques for measurements of thermal conductivity of geological media are: 1) the thermal comparator (or divided-bar) method which is a steady-state method and is used for core samples, such as rocks; 2) the needle-probe method which is a transient method and is suitable for unconsolidated samples such as sands.

Thermal Comparator (Divided-Bar) Method

The sample or specimen in the form of a circular or square parallel-faced flat plate is sandwiched between two standards (reference

materials of known thermal conductivity) of dimensions equal to those of the specimen. This "stack" is surmounted by a heating element. To minimize the radial heat losses to the surroundings, an outer cylindrical guard tube with a number of heating elements in it is put around the specimen-standards stack. The space between the guard tube and the stack is filled with thermal insulation. Thermocouples inside the standards and sample measure the difference in temperature across each of these materials.

A version of the thermal comparator method as it appears in [10] is shown in Figure 1. Determination of the thermal conductivity of the specimen, λ_x , is based on the assumption that the heat flow across the standard is equal to the heat flow across the sample, i.e.

$$\dot{Q} = -\lambda A \frac{\partial T}{\partial l} = -\lambda_x A \frac{\partial T_x}{\partial l} \quad (1)$$

(λ = thermal conductivity of the standard; A = cross sectional area of the specimen and the standard; $\frac{\partial T}{\partial l}$ = temperature gradient down the standard; $\frac{\partial T_x}{\partial l}$ = temperature gradient down the sample).

In a first approximation, from (1), it can be written that:

$$\lambda \frac{\Delta T}{\Delta l} = \lambda_x \frac{\Delta T_x}{\Delta l} \quad (2)$$

Since the distance Δl along which the temperature difference is measured is the same for both the standard and the specimen, then (2) becomes:

$$\frac{\lambda_x}{\lambda} = \frac{\Delta T}{\Delta T_x} \quad (3)$$

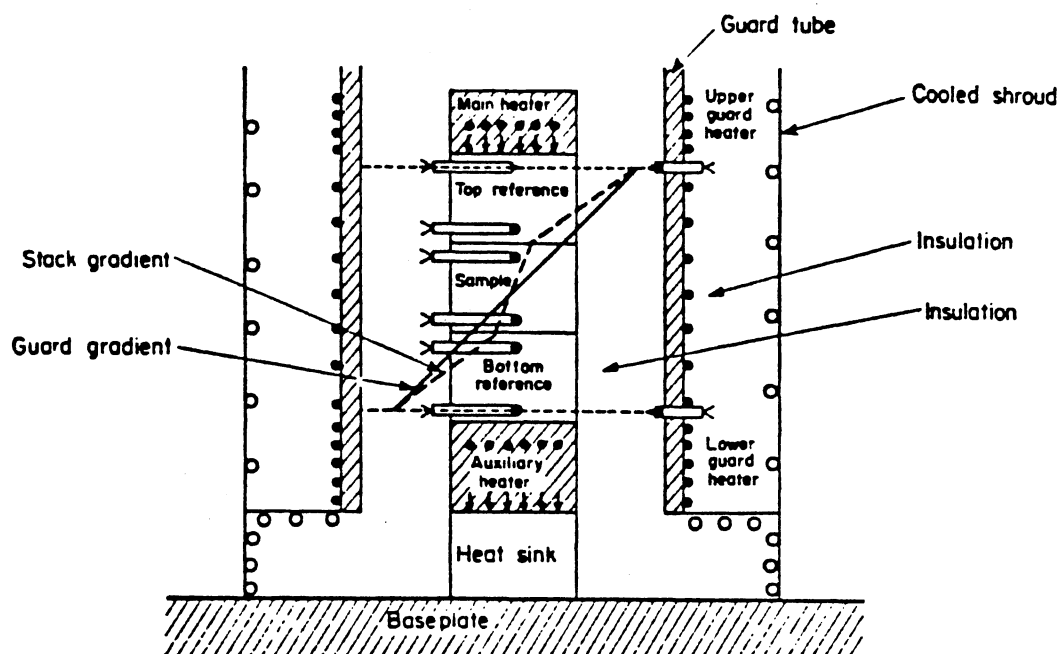


Figure 1. Thermal Comparator Method: Schematic Assembly

Therefore, to a first approximation, the ratio of the conductivity of the specimen to the conductivity of the standard is equal to the ratio of the temperature difference across the standard to the temperature difference across the specimen and λ_x can thus be determined. There are two effects the divided-bar method suffers from and which affect the accuracy of the measurements: 1) conductivity mismatch between the specimen and the standards; 2) interfacial resistance between specimen and standards. The former affects the heat flow through the specimen and standards which in this method is considered the same in determining the thermal conductivity. However, analysis conducted on this method have shown that in practice, the heat flow through the specimen and standards is never the same due to radial heat exchanges between the test stack and the insulation, and also due to the fact that the direct longitudinal heat flow through the insulation can "shunt" the flow through the test sample (i.e. heat bypassing the specimen through the insulation or bypassing the insulation through the specimen, depending on whether the conductivity of the sample is less or more than that of the standards). And these problems become more significant when the thermal conductivities of the specimen and the standards approach that of the insulation, which is always the case when measurements are done on geological media which typically have low conductivities. A complete analysis of these errors can be found in [7].

The interfacial resistance affects the temperature distribution on both the sample and the standards since there is always a temperature drop across the thermal resistances which appear at the contacting surfaces of the specimen and standards. Apart from the two special sources of error mentioned above, the divided-bar method is also subject

to most of the errors pertinent to the absolute steady-state temperature methods, and therefore it is less accurate. For this reason, the thermal comparator (divided-bar) method is largely regarded as a compromise which sacrifices accuracy for the simplicity of sample configuration and relative ease of assembly and operation.

Needle-Probe Method

This method uses a line heat source (i.e. a wire through which a constant electric current passes) and a thermocouple which are embedded alongside each other in the test sample. After the assembly is at a uniform and constant temperature, a constant power is supplied to the heater for a short time and the rise in temperature is recorded. The rise in temperature is determined by the ability of the sample to conduct the heat generated away from the line source. The thermal conductivity of the sample can be determined from the temperature-time record and the power input. The theory on which this method is based can be found in [2].

If we consider the application of heat through an infinitely long, thin heat source embedded in an infinite homogeneous material which is initially at equilibrium, then the temperature rise at a point in the material as a function of time while the heater is on is given by:

$$\theta(r,t) = \frac{Q}{2\pi\lambda} I\left(\frac{r}{2(\eta t)^{1/2}}\right) \quad (4)$$

where Q = power input per unit length of source, cal/cm sec; λ = thermal conductivity of the material, cal/cm sec°C; η = thermal diffusivity of the material, cm²/sec; r = radial distance of point from line source,

cm; t = time from the start of heating, sec; and

$$I(x) = C - \ln x + \frac{x^2}{2} - \frac{x^4}{8} + \dots$$

where C = Euler's constant (0.5772). If $x = \frac{r}{2(\eta t)^{1/2}}$ is small, i.e., large t and small r , then the terms of the order of x^2 and above can be neglected and

$$\theta = \frac{Q}{2\pi\lambda} \left[C - \ln \frac{r}{2(\eta t)^{1/2}} \right] \quad (5)$$

If t_1 and t_2 are two sufficiently long times during the heating interval, the corresponding temperature rise is given by

$$\Delta\theta = \theta_2 - \theta_1 = \frac{Q}{4\pi\lambda} \ln\left(\frac{t_2}{t_1}\right) \quad (6)$$

Then λ is given by

$$\lambda = \frac{Q}{4\pi\Delta\theta} \ln\left(\frac{t_2}{t_1}\right) \quad (7)$$

A plot of the temperature rise $\Delta\theta$ versus the logarithm of time $\left(\frac{t_2}{t_1}\right)$ gives a straight line with a slope of $\frac{Q}{4\pi\lambda}$. Thus λ can be obtained by the knowledge of this slope and of the applied power per unit length of the heat source.

Although the above theory applies to a perfect line heat source (i.e. infinitely large length to diameter ratio), it was shown that the errors in this respect are negligibly small for probes of length to diameter ratio of 30 or more. The theory also applies to samples of infinite dimensions; it was shown that if the testing time interval is limited to the time before the heating effect reaches the surface of the sample, then a sample of practical dimensions behaves as one infinite in

size.

A diagram of a thermal conductivity probe, as shown in [10] is given in Figure 2.

In the following chapters, a pulse method for determination of thermal diffusivity of geological media, as well as the results of measurements on several sedimentary rocks, will be presented.

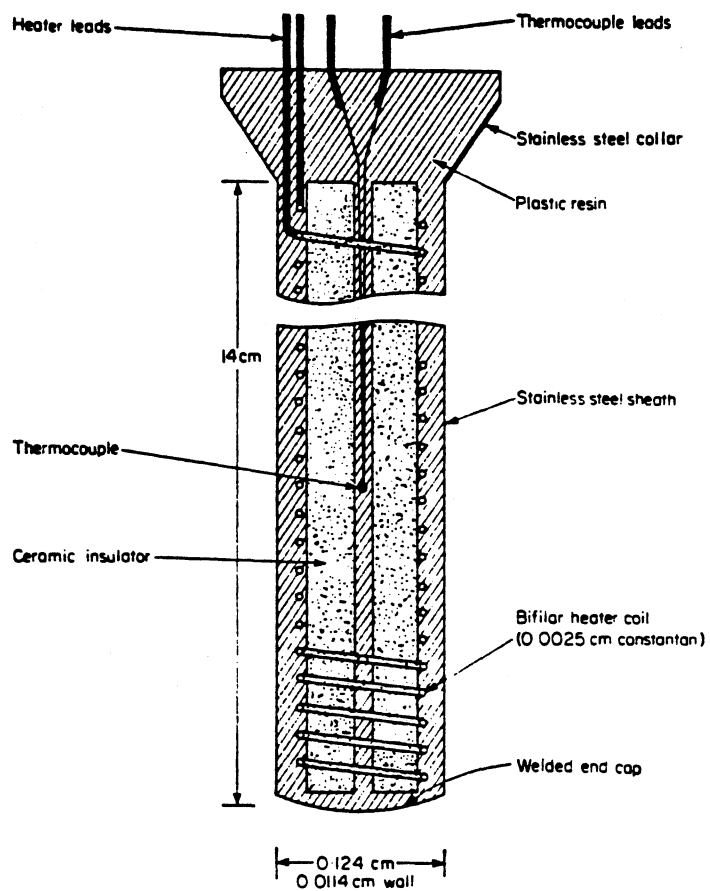


Figure 2. Schematic Diagram of Thermal Conductivity Probe

CHAPTER II

EXPERIMENTAL PROCEDURE

One of the thermal transport properties of a solid is its thermal diffusivity, η , which governs the temperature profile of a solid through the diffusion equation:

$$\frac{\partial T}{\partial t} = \eta \nabla^2 T \quad (8)$$

where T is the temperature and t is time. Solutions to this diffusion equation for a variety of sample shapes and boundary conditions are given in [2].

The thermal diffusivity, η , and thermal conductivity, λ , of a solid are related by:

$$\eta = \frac{\lambda}{\rho c} \quad (9)$$

where ρ is the mass density and c is the specific heat of the solid.

In this work, the thermal diffusivity was determined from the diffusion equation (8) by a pulse method. This method is an adaptation using computer control and modern digital instrumentation of an earlier technique first used for the study of thermal transport properties in metals and semiconductors at high temperatures [3].

Apparatus

The samples used are sedimentary rocks in the shape of cylinders of 2.5 cm in diameter and 4 to 8 cm in length. A heater located at one end of the sample creates, when energized for a short time, a one-dimensional heat pulse through the sample. Both the sample and the heater are enclosed by a furnace connected to a programmable temperature controller (Omega CN 2000). The furnace provides the ambient temperature at which the diffusivity is desired. A block diagram of the apparatus is shown in Figure 3. The heater is turned on and off through the computer which actuates a relay in the data acquisition unit, DAC (HP 3412A). Three thermocouple wells 0.9 mm in diameter were drilled along the length of the sample. The distance separation between the three thermocouple wells was chosen to be 5 mm in order to allow response to the heat pulse by all three thermometers when the thermal diffusivity of the sample is low (of the order of $10^{-2} \text{ cm}^2/\text{sec}$) as it is for sedimentary rocks. The thermometers used were type K thermocouples and electronic ice points were used as the reference junctions. The thermocouples were monitored, under computer control, by digital voltmeters (HP 3478A), DVM, with a sensitivity of 0.1 μV . This gives a temperature measurement sensitivity of $\sim 3\text{mK}$ near room temperature.

Procedure

After the sample is brought to steady-state conditions at the temperature where the diffusivity is desired, the computer triggers the voltmeters and records the initial readings of the thermometers. It then closes the relay, turning the heater on. A one-dimensional heat pulse now flows through the sample, and the temperature is monitored as

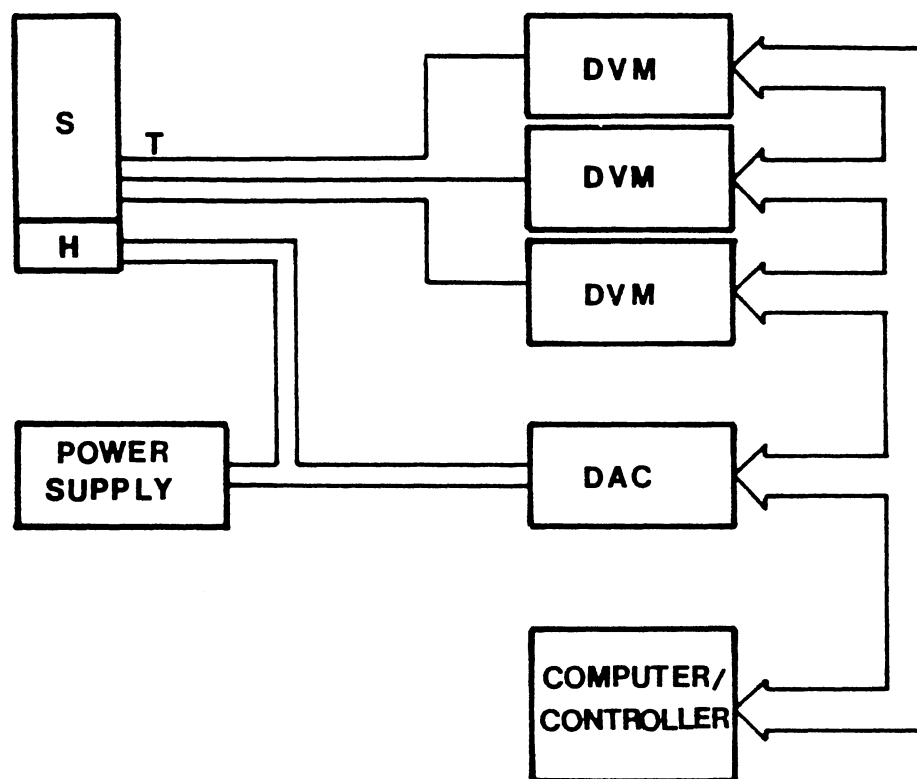


Figure 3. Block Diagram of the Apparatus. The Temperature Profile in the Sample S is Sensed by the Thermocouples T and Digital Voltmeters DVM after the Heater H is Activated by the Data Acquisition Unit DAC. The Sample and Heater are Enclosed in a Furnace not Shown

a function of time. To do this, the computer triggers simultaneously the three voltmeters at regular intervals, which in this experiment were 0.5 seconds. The temperature readings of the three thermometers are thus collected every 0.5 seconds and stored in the computer. Data are collected for a time interval of 30 to 100 seconds, during which the temperature at the thermometer nearest the heater rises by 1 to 5 K. It is desired that the data acquisition times be short so as to minimize the possibility of electronic drift. When data collection is completed, the relay in the data acquisition unit, DAC, is automatically opened by computer command, thus turning off the heater. The computer now reduces the data stored during the process of data acquisition and displays the thermal diffusivity.

The simple one-dimensional diffusion equation

$$\frac{\partial T}{\partial t} = \eta \frac{\partial^2 T}{\partial x^2} \quad (10)$$

applies to the region of interest which is the part of the sample between the lowest and the highest thermocouples. A plot of $\frac{\partial T}{\partial t}$ versus $\frac{\partial^2 T}{\partial x^2}$ for the mid-plane between these two thermocouples is made. The thermal diffusivity is given by the slope of the least squares regression line for this plot.

The data reduction process starts with the conversion of the voltmeter readings to temperatures using an interpolation formula for the thermocouple tables. The initial thermometer readings are subtracted from each point in the data set to eliminate any small mismatch between the thermocouples. The rate of change of the temperature with time $\left(\frac{\partial T}{\partial t}\right)$ at the mid-plane is approximated by the slope of the regression

line for a small subset of the data, and this value is assigned to the mid-point of the time interval of the subset. The value of $\frac{\partial^2 T}{\partial x^2}$ at the mid-plane at this time is approximated by the finite difference relation:

$$\frac{\partial^2 T}{\partial x^2} = \frac{[T_U(t) - T_M(t)] - [T_M(t) - T_L(t)]}{(\Delta x)^2} \quad (11)$$

where Δx is the distance between adjacent thermometers and the subscripts U, M, L refer to the upper, middle and lower thermometers respectively. This way, a set of values for $\frac{\partial T}{\partial t}$ and the corresponding $\frac{\partial^2 T}{\partial x^2}$ are obtained for the mid-plane. These values are fitted by least squares to obtain the thermal diffusivity, η .

Typical curves for the variation of temperature as a function of time are shown in Figure 4. Figure 5 displays a plot of $\frac{\partial T}{\partial t}$ versus $\frac{\partial^2 T}{\partial x^2}$, the straight line being the least squares regression line. It can be seen that the experimental points follow closely the linear relation expected from the diffusion equation (10).

The thermal conductivity, λ , of the sample was calculated using (9) after the density and specific heat of the sample were determined. Since the samples were right circular cylinders, the density was determined from the mass and the dimensions of the sample. To measure the specific heat of the samples, a simple drop calorimeter was constructed. The sample, heated to the steam point, was rapidly transferred to an insulated water bath at room temperature and the temperatures of both the bath and the sample were monitored until final equilibrium was attained. The specific heat was calculated by straight forward application of the first law of thermodynamics, heat losses to

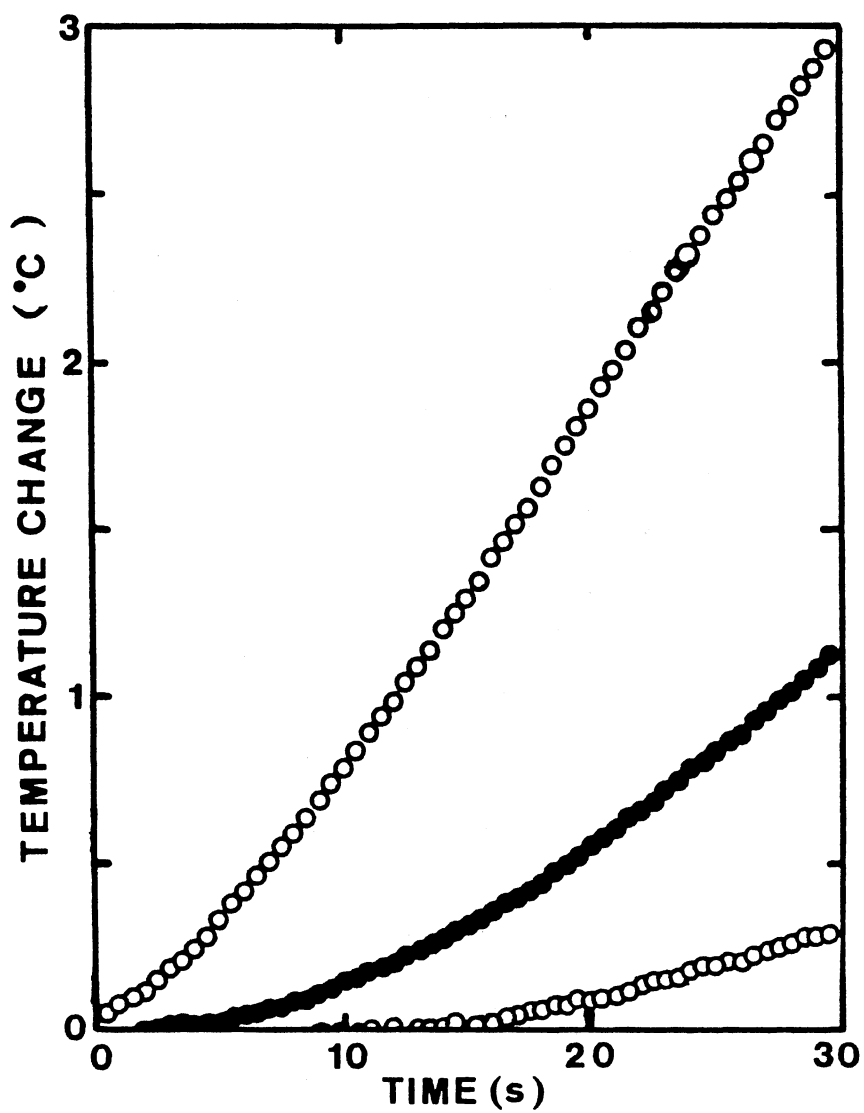


Figure 4. Typical Temperature vs. Time Curves for the Three Thermometers. The Upper Curve is from the Thermometer nearest the Heater; and the Lower, from that farthest from the Heater

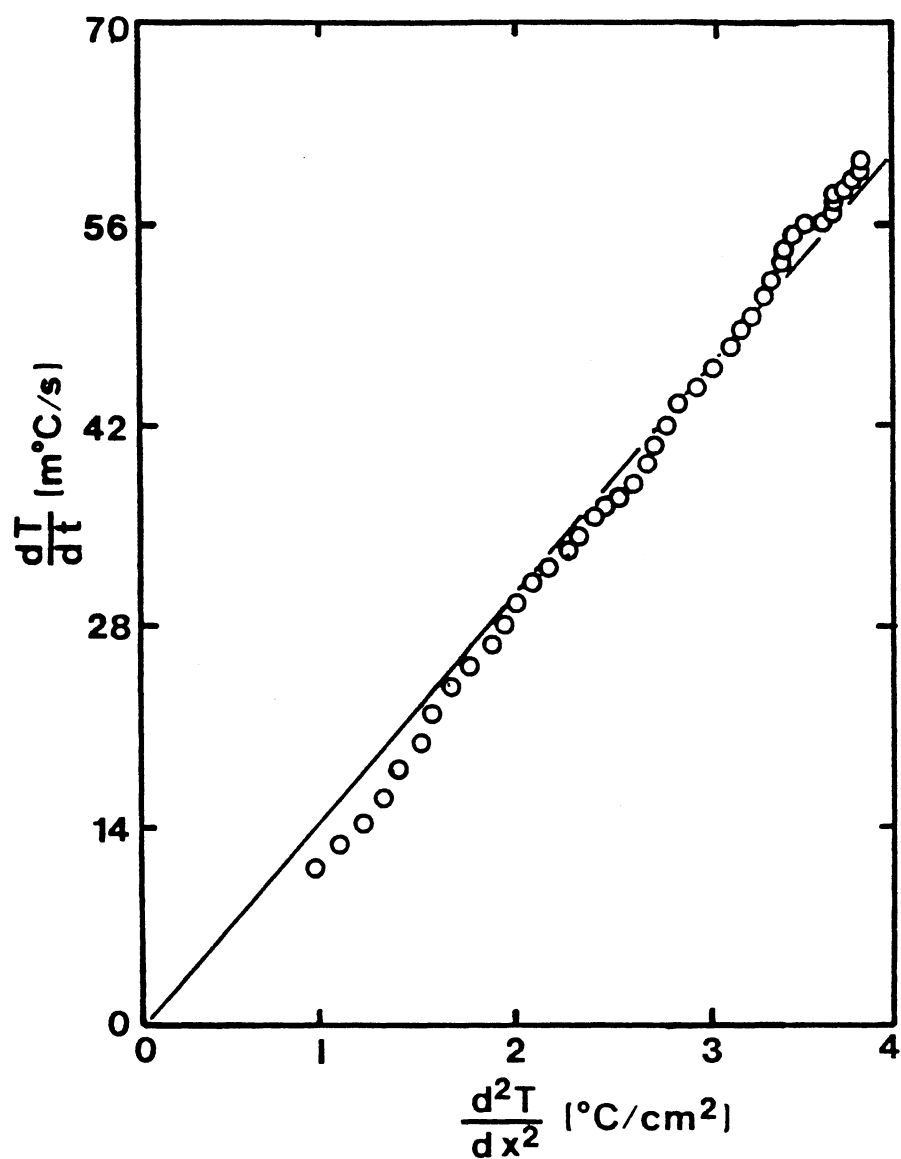


Figure 5. Rate of Change of the Temperature vs. its Second Space Derivative Calculated from the Data in Figure 4. The Slope of the Regression Line is the Thermal Diffusivity

the surroundings being neglected.

The pulse method presented here, like all other transient temperature methods for measuring thermal diffusivity, has the advantage of being much faster than the steady-state methods which determine the thermal conductivity directly from Fourier's Law:

$$J = -\lambda \nabla T \quad (12)$$

where J is the thermal current density and T is the temperature. Since J and ∇T must be constant over the measurement volume, such methods are complicated by two problems: 1) the necessity of rigorous steady-state conditions which makes the collection of data, and thus the method, become very slow because the thermal equilibrium times are very long (of the order of hours) at elevated temperatures; 2) the necessity of controlling accurately the heat losses through complicated guarding systems to shield against such losses and/or correction of the experimental data for such losses.

The pulse method, being a dynamic method, does not require rigorous steady-state conditions, and this reduces sharply the time necessary for a measurement. Unlike the steady-state methods which require measurements of the heat flux and the temperature gradient through the sample, this method requires only the measurement of the time interval in which a heat pulse propagates a known distance. And in principle, lengths and time intervals can be more accurately and more easily measured than heat fluxes and temperature gradients.

Due to the fact that the samples used have typically low thermal conductivities and also because the region of interest is the part of the sample between the lowest and the highest thermocouples (which are

10 mm apart), the heat losses through the lateral surface of the sample in the region of interest are, to a first approximation, negligibly small and therefore there is no need for corrections for heat losses through radiation or convection.

The method has, however, a few sources of error: 1) the degree of precision in measuring the distances at which the three thermocouple wells are drilled is probably the most significant source of error, considering that, due to reasons shown already, the spacing between the thermocouple wells was chosen to be 5 mm and therefore an imprecision of a few tenths of a mm becomes significant. This is a systematic error that appears in the measurements of all samples used; 2) there are also random errors due to the scattering of the experimental data with respect to the least squares regression line; 3) finally, there is an error involved in measuring the specific heat due to neglect of heat losses to the surroundings. This last affects the calculated conductivity λ , but not the diffusivity α .

Based on multiple measurements done on several samples, the errors are estimated to be approximately 5% each for the thermal diffusivity and the specific heat measurements.

CHAPTER III

EXPERIMENTAL RESULTS AND DISCUSSION

Standardization of the Apparatus

The thermal diffusivities and thermal conductivities were determined by the pulse method described in the previous chapter for four homogeneous materials whose thermal conductivities span the range that one expects to encounter for sedimentary rocks (10^{-2} - 10^{-1} W/cmK). These materials were: synthetic crystalline quartz, fused quartz glass, type 304 stainless steel and plastic lexan, which is a polymeric glass. For steel and lexan, specimens were prepared in the shape of cylinders one inch in diameter and two inches in length, to approximate the shape and dimensions of the sedimentary rock samples. For quartz crystal and quartz glass samples, large specimens were not available; the crystal (α -quartz) sample was a square rod 5mm on a side and 5cm long with its long dimension perpendicular to the optic axis. The fused quartz (g-SiO₂) sample was a circular rod 10cm long and 5 mm in diameter. Because of the smaller diameter of these two samples, instead of drilling thermocouple wells inside the samples at 5mm intervals, as was done for all other samples, the thermocouples were mounted on the surface of the quartz samples at 5mm intervals.

Table I shows the thermal diffusivities, specific heats and densities measured for these standard materials as well as the thermal conductivity calculated from these using (9).

Table II shows the thermal diffusivities and thermal conductivities of these materials as reported in the literature.

The measured values agree with the corresponding reference values to within 10%. In fact, except for lexan, the agreement is to within 5% or better, which is less than the experimental errors of this method, estimated from multiple observations, to be 5% each for the thermal diffusivity and specific heat measurements.

TABLE I
THERMAL PROPERTIES OF STANDARD MATERIALS:
OBSERVED VALUES

Material	Thermal Diffusivity (cm ² /sec)	Specific Heat (cal/gK)	Density (g/cm ³)	Thermal Conductivity (W/cmK)
α -Quartz (\perp c-axis)	0.0324	0.17	2.65	0.064
Type 304 Stainless Steel	0.0389	0.122	7.90	0.157
SiO ₂ Glass	0.0089	0.17	2.22	0.014
Lexan (polycarbonate Glass)	0.00145	0.29	1.19	0.0021

TABLE II
THERMAL PROPERTIES OF STANDARD MATERIALS:
REFERENCE VALUES¹

Material	Thermal Diffusivity (cm ² /sec)	Thermal Conductivity (W/cmK)
α -Quartz (\perp c-axis)	0.031	0.062
Type 304 Stainless Steel	---	0.152
SiO ₂ Glass	0.0085	0.0142
Lexan (Polycarbonate Glass)	---	0.0019 ²

¹ Reference values taken from [11].

² Gross, S., Modern Plastics Encyclopedia, (McGraw-Hill, New York, 1971), p.561.

Experimental Results and Conclusions

The temperature dependence of the thermal diffusivity of six different sedimentary rocks was measured over a temperature range of practical interest in geology (i.e. from 20° C to 100° C). The rocks studied were: two carbonates (a packstone and a mudstone), berea sandstone, two limey sandstones, and dolomitic sandstone. The sandstones are generally rich in quartz (up to about 60%) which is found in both

small crystallites and amorphous form. Dolomitic sandstones have, besides quartz, a significant content of calcium and magnesium carbonates. The carbonate packstone and mudstone are part of the larger family of limestones. Limestones are rich in calcium and magnesium carbonates (60-80%), mudstones being finely grained while the packstones contain large crystallites. Apart from the minerals mentioned above, each of these types of rocks contains also small amounts of other miscellaneous minerals, both in amorphous and small crystallites form, depending on the age and geological history of the sedimentary basins the rock comes from.

The well-known result from the kinetic theory of gases:

$$\lambda = \frac{1}{3} C v L \quad (13)$$

was first applied by Debye to describe thermal conductivity in dielectric solids, with C = the heat capacity per unit volume of the phonons, v = phonon velocity, L = phonon mean free path and λ = thermal conductivity [4].

In the Debye approximation (where the phonon velocity v is considered constant for all polarizations), the phonon heat capacity at high temperatures (i.e. $T > \theta_D$, where θ_D = Debye temperature) approaches a constant value (i.e. the classical value of $3Nk_B$ of Dulong and Petit, where N is the number of atoms in the specimen and k_B is Boltzman constant). Therefore, the behavior of λ at high temperatures is determined by the phonon mean free path, L .

In crystals, the phonon mean free path L is determined by two processes: geometrical scattering (i.e. scattering by lattice imper-

fections and by crystal boundaries), and scattering by other phonons.

The requirement of conservation of wavevector in crystals is expressed for the three phonon processes by:

$$\vec{k}_1 + \vec{k}_2 = \vec{k}_3 + \vec{G} \quad (14)$$

where \vec{k}_i ($i = 1, 2, 3$) is the wavevector of a phonon and \vec{G} is a reciprocal lattice vector. Processes in which $\vec{G} = 0$ are called normal processes while those in which $\vec{G} \neq 0$ are called Umklapp processes.

At high temperatures, the dominant processes that cause thermal resistivity ($1/\lambda$) in a crystal are the three phonon Umklapp processes. These processes do not conserve the total momentum of a phonon gas, changing, therefore, the resultant heat flow through a crystal. Thus, Umklapp processes are capable of bringing the distribution of phonons into local thermal equilibrium (i.e. the phonons at one end of the crystal being in thermal equilibrium at a temperature T_2 and those at the other end in equilibrium at another temperature, T_1). The three phonon normal processes do not play a direct role in producing thermal resistivity because they leave the total momentum of a phonon gas unchanged and therefore produce very little change (none in the absence of dispersion) in the heat flow through a crystal.

The energy of phonons \vec{k}_1 and \vec{k}_2 suitable for Umklapp processes to occur is of the order of $\frac{1}{2} k_B \theta_D$ because each of the colliding phonons must have wavevectors of the order of $\frac{1}{2} G$ in order for the collision (14) to be possible. At high temperatures (i.e. $T > \theta_D$), most phonons have energies high enough for Umklapp processes to occur and therefore these are the dominant resistive processes in a crystal.

The phonon mean free path at high temperatures is therefore determined by the relaxation time associated with Umklapp processes.

The three-phonon processes are caused by the anharmonic coupling between different phonons (i.e. the third-order terms in the lattice potential energy). The theory of the effect of anharmonic coupling on thermal resistivity predicts that the mean free path is proportional to $1/T$ at high temperatures in agreement with many experiments [6]. This can be explained by the fact that the total number of excited phonons at high temperatures is proportional to T and the collision frequency (i.e. $1/\tau$, where τ is the relaxation time) of a given phonon is proportional to the number of phonons with which it can collide, therefore

$$\frac{1}{\tau} \sim T \quad (15)$$

and since $L = v\tau$, this implies that

$$L \sim \frac{1}{T} \quad (16)$$

Therefore, the thermal conductivity of crystals is proportional to $1/T$ at high temperatures.

In amorphous substances, the thermal conductivity at high temperatures increases slightly with temperature. This can be explained by the fact that, at such temperatures, the heat conduction is due to localized phonons. With an increase in temperature, the number of local phonons being able to overcome an energy barrier and hop from one site to another increases and therefore the thermal conductivity increases.

Due to the specific structure of the sedimentary rocks which contain minerals in grains of different sizes the heat conduction at high temperatures can be attributed to the fact that phonons localized in the

small crystallites inside the rock hop from one crystallite to another.

Since the specific heat and the density of the sedimentary rocks are only very weakly temperature dependent over the temperature range considered (i.e. 20°C to 100°C), it can be concluded that the thermal conductivity over this temperature range varies in a similar manner to the diffusivity variation with temperature. With regard to this, it is interesting to note that using (9) and (13) we get the result:

$$\eta = \frac{\lambda}{C} = \frac{1}{3} v L \quad (17)$$

This shows that, at high temperatures, the phonon mean free path, L , affects the thermal diffusivity in the same way it affects λ , which was discussed earlier.

Figures 6 and 7 show the variation of thermal diffusivity with temperature for the two carbonates (packstone and mudstone). The solid straight line is a guide to the eye and the dotted line represents the $1/T$ curve. The thermal diffusivity, and therefore the thermal conductivity, for these two rocks decrease with temperature at a rate slower than $1/T$ which is an indication that in these materials the limiting thermal resistivity is between the crystallites rather than inside the grains.

Figures 8, 9 and 10 show the diffusivity variation with temperature for the two limey sandstones and for dolomitic sandstone, respectively. In these rocks a nearly $1/T$ temperature dependence of the diffusivity, and therefore of the thermal conductivity, is observed which suggests a crystal-like behavior in terms of heat conduction. This indicates that

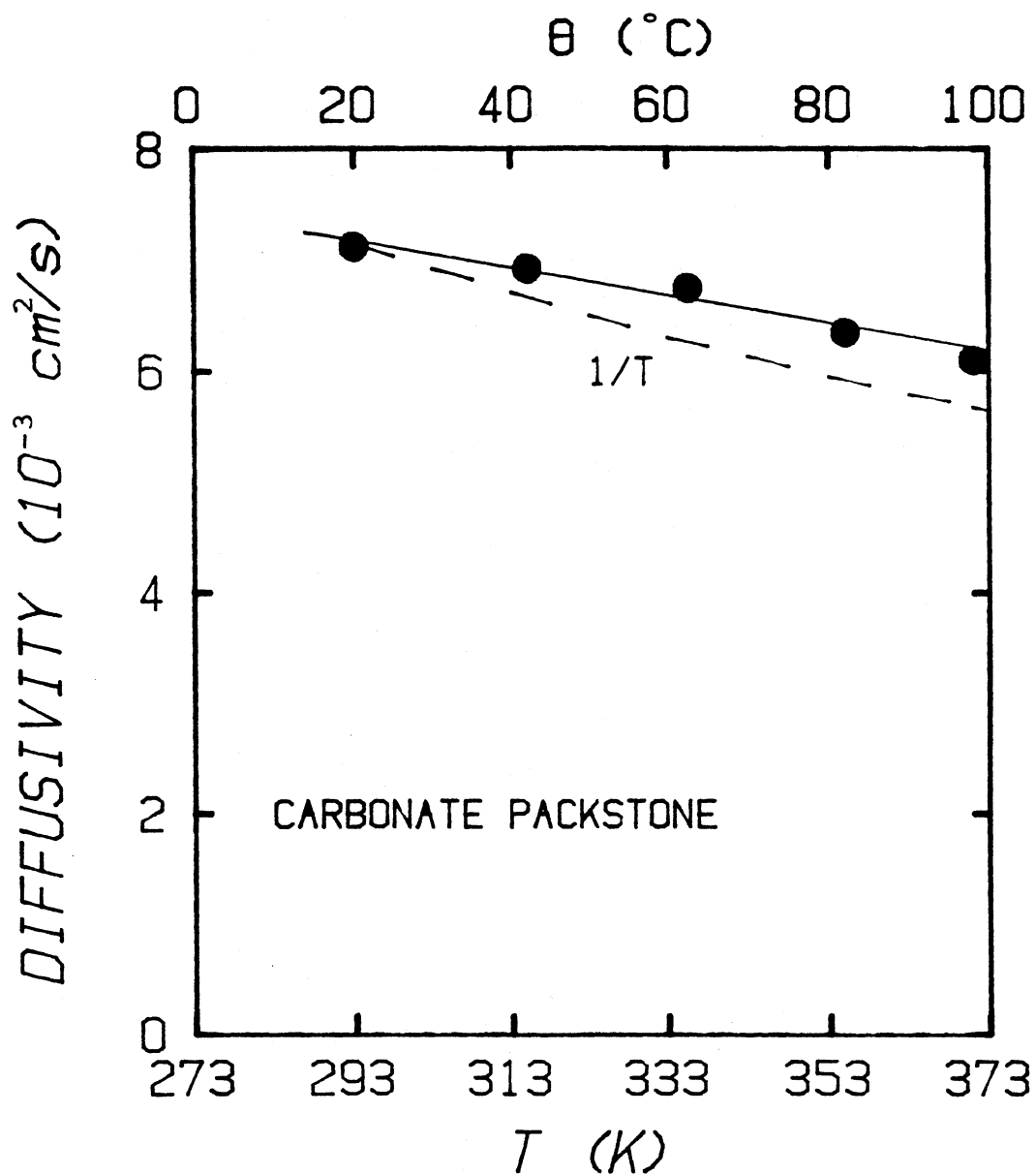


Figure 6. Thermal Diffusivity of Carbonate Packstone as a Function of Temperature. The Solid Line is a Guide to the Eye

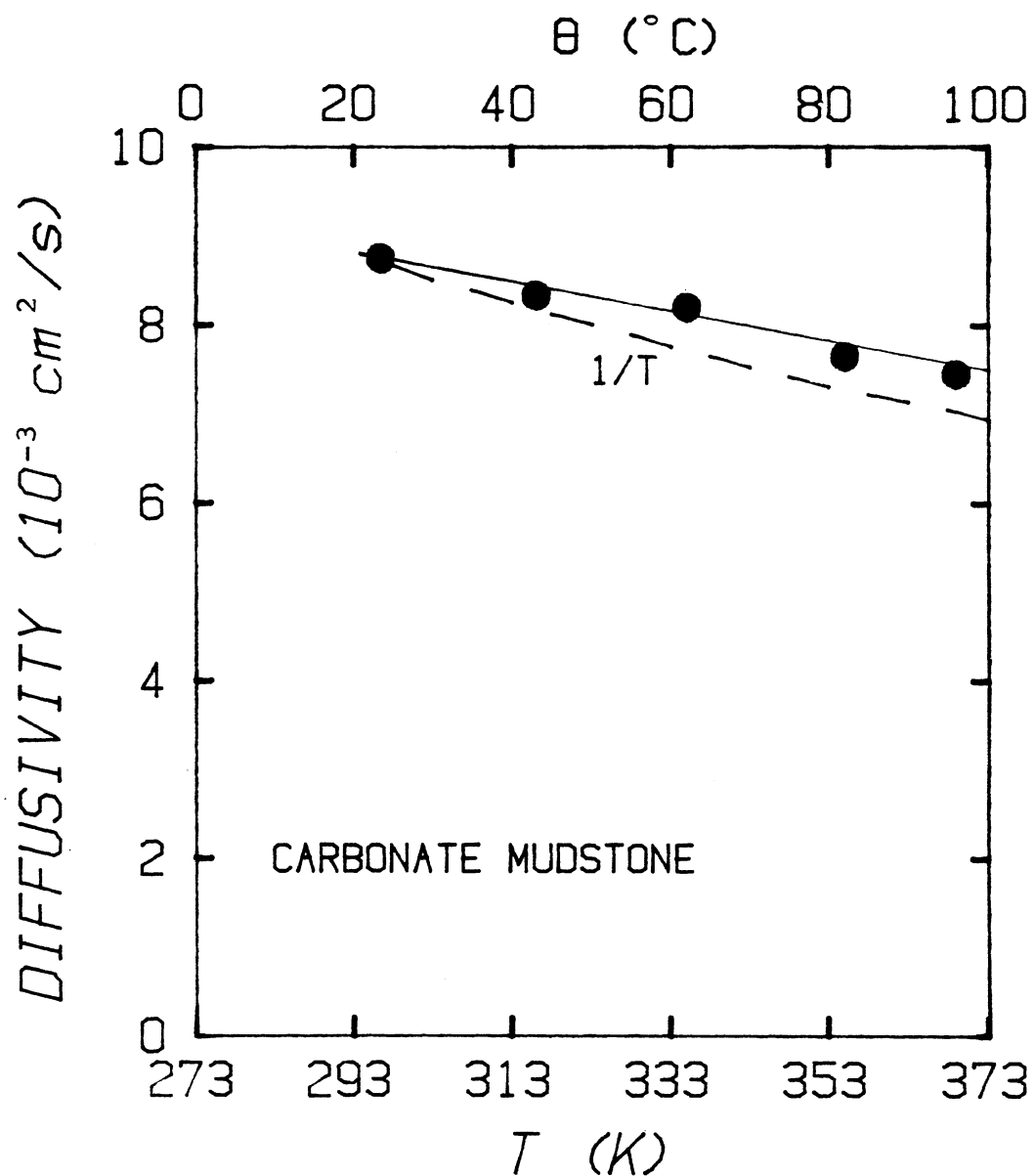


Figure 7. Thermal Diffusivity of Carbonate Mudstone as a Function of Temperature. The Solid Line is a Guide to the Eye

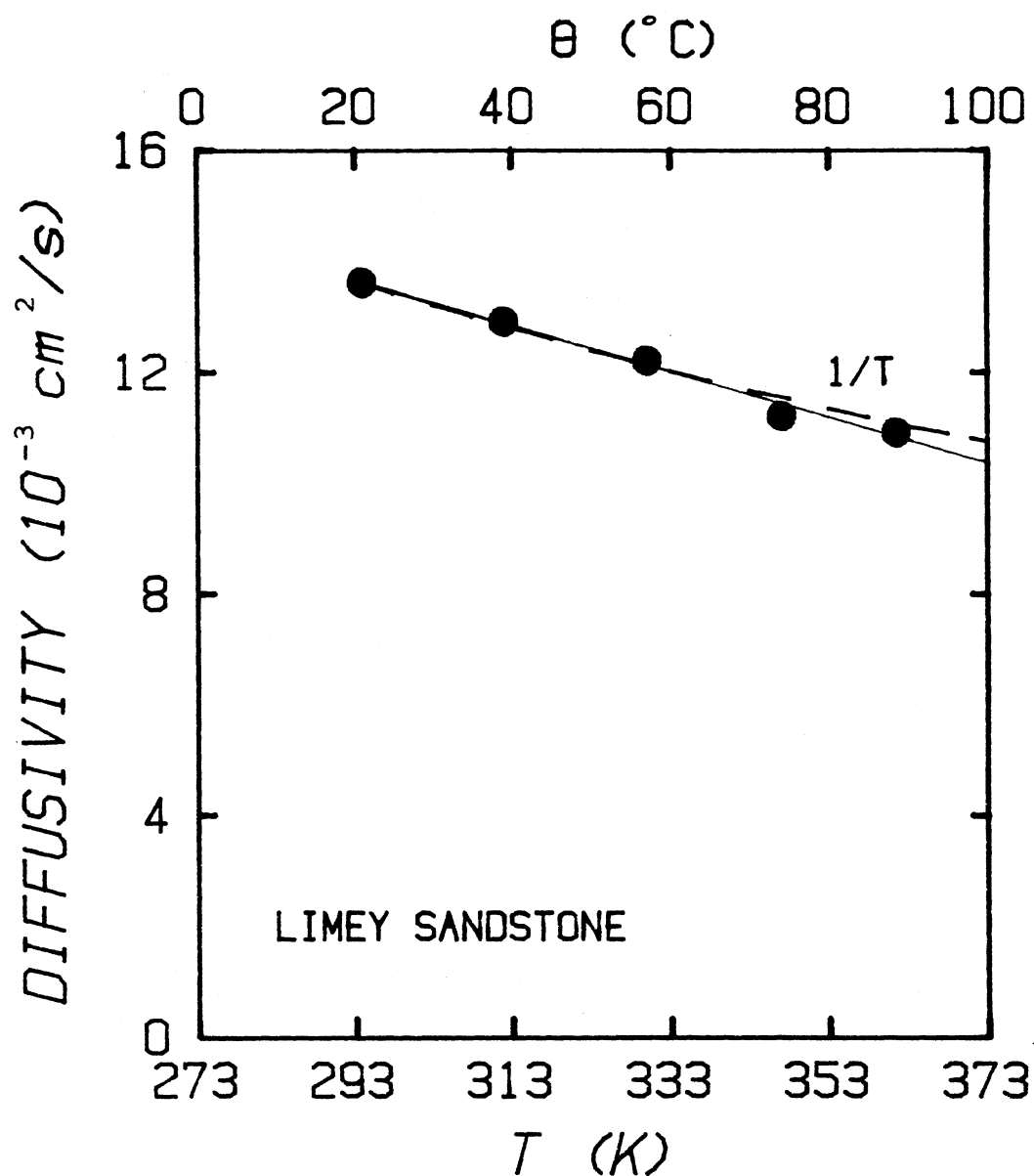


Figure 8. Thermal Diffusivity of Limey Sandstone as a Function of Temperature. The Solid Line is a Guide to the Eye

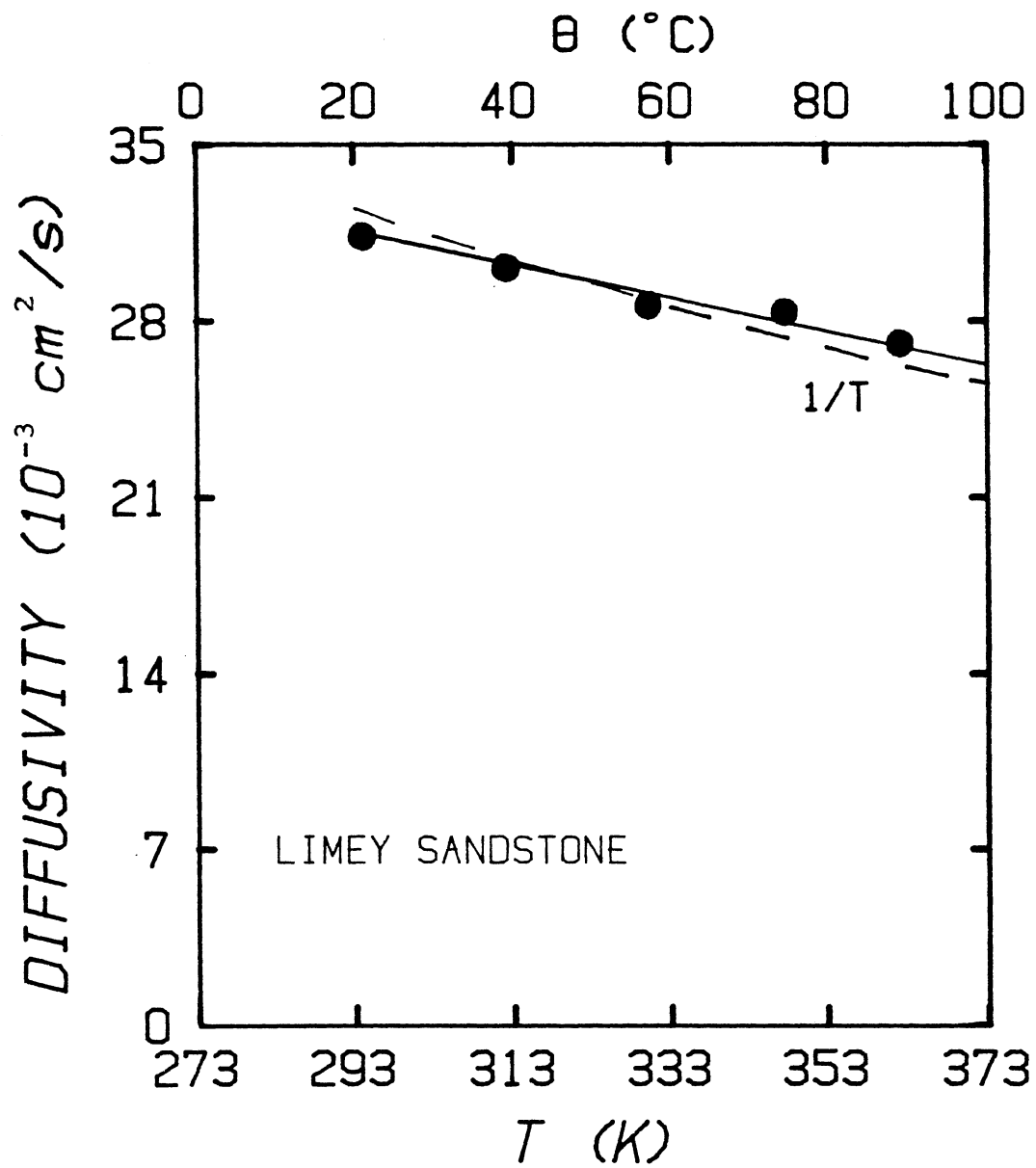


Figure 9. Thermal Diffusivity of Limey Sandstone as a Function of Temperature. The Solid Line is a Guide to the Eye

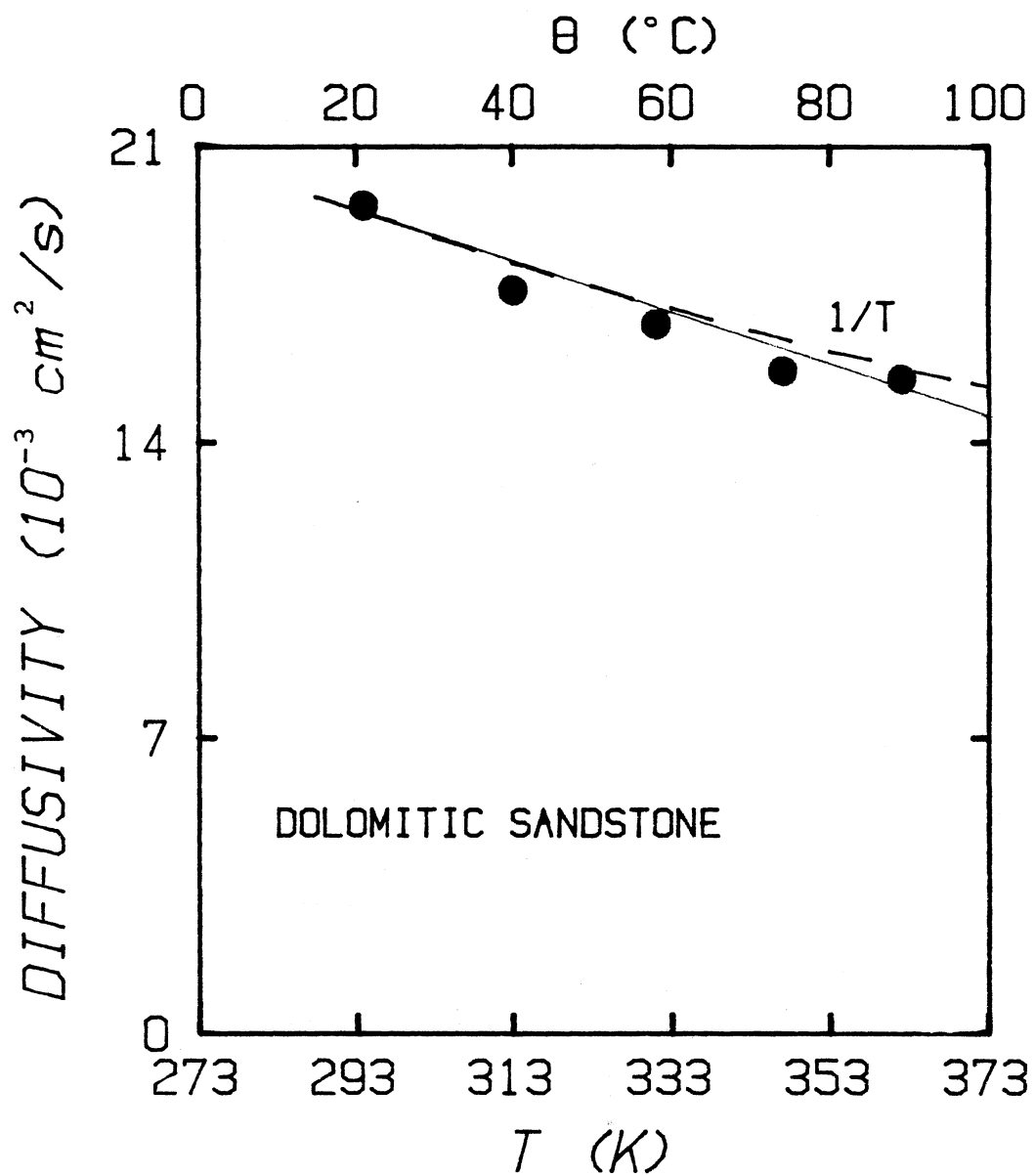


Figure 10. Thermal Diffusivity of Dolomitic Sandstone as a Function of Temperature. The Solid Line is a Guide to the Eye

the limiting thermal resistivity in these rocks may be inside the grains.

Berea sandstone shows a behavior in-between the two distinct groups discussed above: the temperature dependence of thermal diffusivity is not as weak as in carbonates, but not as close to a $1/T$ dependence as in dolomitic sandstone and limey sandstones.

In summary, this work has shown that the pulse thermal diffusivity measurements using modern digital instrumentation and computer control provide a practical and accurate method for the determination of the thermal transport properties of geological materials and other solids of similar thermal conductivity.

The study of the temperature dependence of the thermal diffusivity in sedimentary rocks has shown basically two types of behavior: 1) a nearly $1/T$ dependence which indicates that the heat conduction is limited within the grains; 2) a decrease of diffusivity with temperature slower than $1/T$, case in which the weaker the temperature dependence of the diffusivity, the stronger is the indication that the transfer of heat is limited between the grains.

It was also observed that the higher diffusivity rocks display a stronger and closer to $1/T$ temperature dependence of the thermal diffusivity. Indeed, for all the six rocks studied, a consistent trend is observed, which shows that the higher the thermal diffusivity is, the closer to $1/T$ its temperature dependence becomes.

Finally, the measurement of thermal diffusivity of different sedimentary rocks over a temperature range of 20°C to 100°C clearly shows that the diffusivity, and therefore the thermal conductivity, is not constant, but decreases with temperature: a drop of 14-21% was observed

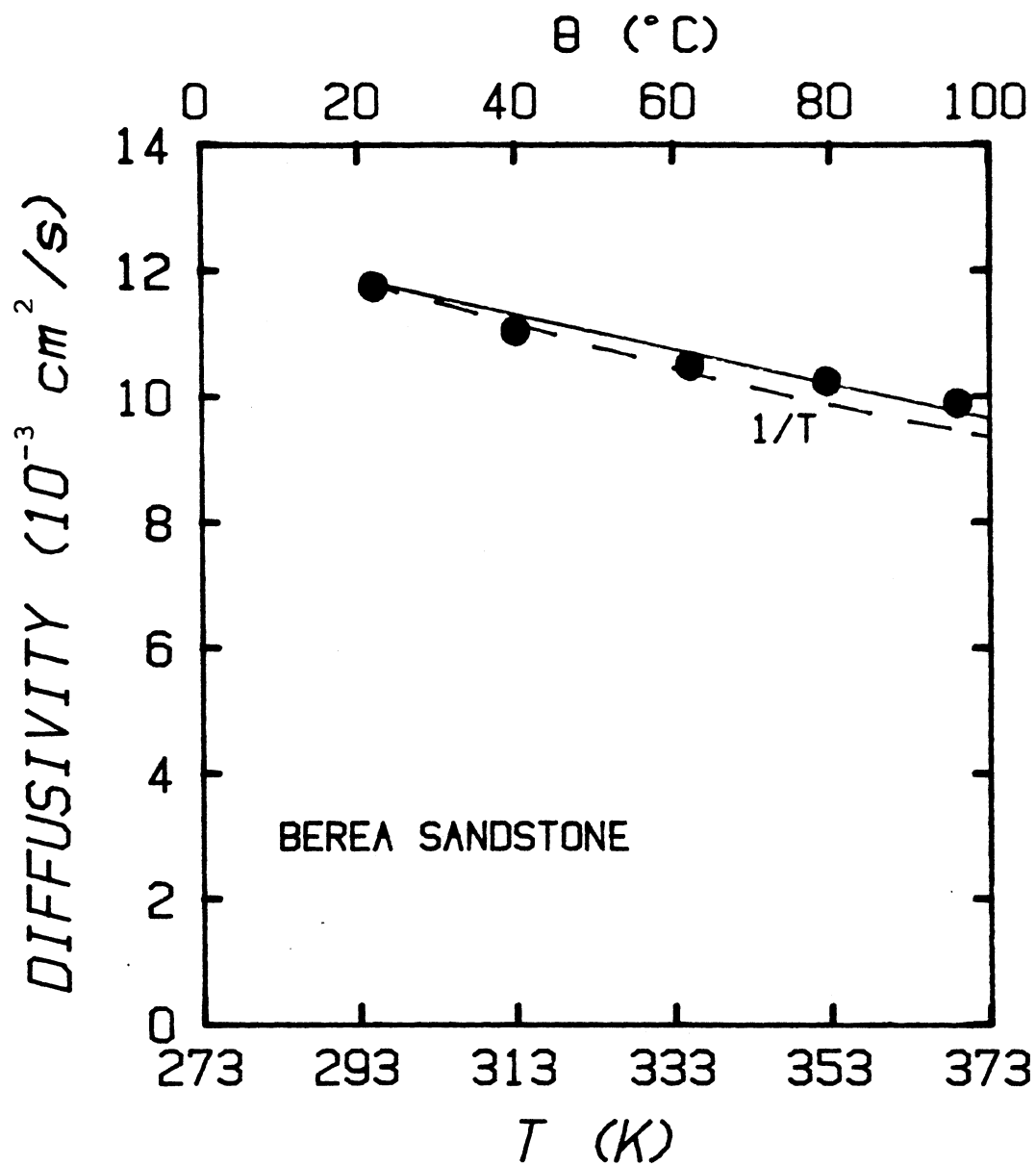


Figure 11. Thermal Diffusivity of Berea Sandstone as a Function of Temperature. The Solid Line is a Guide to the Eye

for the six rocks studied. This shows the importance of knowing the relation between the thermal diffusivity and temperature over a range of practical interest.

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APPENDIX

DATA ACQUISITION AND CONTROL PROGRAM

```

10 ! THERMAL DIFFUSIVITY -- MAIN PGM
20 COM t1(200),t2(200),t3(200),dtdt(200),d2tdx(200),tdfs(200)
30 COM eta(200),xs(200),yx(200),tc(50),tbar(200)
40 COM runum,jr,tint,dti,dlay,x12,x23,t1,th,dt,NT,runtyp,etabar,sd(200)
50 COM tau
100 DISP "Enter a descriptive title for the experiment" @ INPUT title$
110 DISP "Enter additional information" @ INPUT subtitle$
120 !
130 DISP "Choose a file name for data storage."
140 DISP " USE THE SPECIAL FUNCTION KEYS"
150 ON KEY# 1,"CONOCO" GOTO 800
160 ON KEY# 2,"OTHER" GOTO 900
170 KEY LABEL
180 GOTO 180
190 OFF KEY#
200 ! 200-299 are reserved for alarms
300 WAIT 2000
310 CLEAR
320 DISP "*** CHOOSE THE TYPE OF EXPERIMENT *** "
330 DISP " "
340 DISP "      <f1> Single temperature only"
350 DISP "      <f2> N specified temperatures"
360 DISP "      <f3> Range of temperatures at regular intervals"
365 DISP "      <f4> Several temperatures, manual control"
366 DISP "      <f5> Auto"
370 ON KEY# 1,"SINGLE" GOTO 500
380 ON KEY# 2,"N TEMP" GOTO 600
390 ON KEY# 3,"T RANGE" GOTO 700
395 ON KEY# 4,"MANUAL" GOTO 550
396 ON KEY# 5,"AUTODATA" GOTO 580
400 KEY LABEL
410 GOTO 410
420 OFF KEY#
430 GOTO 1000
500 runtyp$="singlet"
505 runtyp=1
510 GOTO 420
550 runtyp$="singlet"
560 runtyp=4
570 GOTO 420
580 runtyp$="AUTO"
581 runtyp=5
582 GOTO 420
600 runtyp$="ntemp"
605 runtyp=2
610 GOTO 420
700 runtyp$="trange"
705 runtyp=3
710 GOTO 420
800 ! set up Conoco file
810 D$=VAL$(DATE)
820 L$="CONOCO"&D$
830 DISP "The data will be stored as ";L$

```

```

840 GOTO 190
900 D$=VAL$(DATE)
910 DISP "Enter the file name (up to 5 characters)" @ INPUT L$
920 L$=L$&D$
930 DISP " The data will be stored as ";L$
940 GOTO 190
999 !
1000 ! Enter the experimental parameters
1010 CLEAR @ DISP "SET THE PARAMETERS FOR THE DIFFUSIVITY MEASUREMENT"
1020 DISP " "
1030 DISP "Time between temperature measurements (msec)" @ INPUT tint
1040 DISP "Total time for a diffusivity measurement (msec)" @ INPUT deti
1050 DISP "Time delay before starting data acquisition (msec)"
1060 DISP "Distances between thermocouples: x12,x23 (cm)" @ INPUT x12,x23
1070 runum=0
1080 tau=2*tint
1099 !
1100 IF runtyp$="singlet" THEN 1110 ELSE 1200
1102 IF runtyp=1 THEN 1110
1105 CLEAR @ DISP " INSTRUCTIONS FOR A MANUAL RUN"
1106 DISP " " @ GOTO 1120
1110 CLEAR @ DISP "INSTRUCTIONS FOR A SINGLE TEMPERATURE RUN " @ DISP " "
1120 DISP " 1. Set the temperature controller manually to the desired "
1121 DISP " temperature. NOTE THAT THE SETTINGS ARE IN DEG C."
1122 DISP " "
1130 DISP " 2. Wait for the system to equilibrate. "
1131 DISP " "
1140 DISP " 3. Press CONT <f4> when equilibrium has been reached."
1141 DISP " "
1150 DISP " 4. If the desired temperature is room temperature, you may"
1151 DISP " press CONT at once." @ DISP " "
1160 PAUSE
1170 runs=1
1180 GOTO 1500
1200 IF runtyp$="ntemp" THEN 1210 ELSE 1300
1210 CLEAR @ DISP " INSTRUCTIONS FOR SETTING N TEMPERATURES "
1211 DISP " "
1220 DISP " 1. Enter the number of temperatures. " @ INPUT NT
1230 DISP " 2. Enter the ";NT;" temperatures as prompted" @ DISP " "
1240 FOR jt=1 TO NT @ DISP " Temp #";jt;" (deg C) "; @ INPUT tc(jt)
1250 NEXT jt
1260 runs=NT
1270 GOTO 1500
1300 IF runtyp$="trange" THEN 1305 ELSE 1400
1305 CLEAR @ DISP " INSTRUCTIONS FOR SETTING A RANGE OF TEMPERATURES "
1310 DISP " "
1320 DISP " 1. Enter the lowest temperature. (deg C)" @ INPUT t1
1330 DISP " "
1340 DISP " 2. Enter the highest temperature. (deg C)" @ INPUT th
1350 DISP " "
1360 DISP " 3. Enter the temperature interval between points. (deg C)"
1370 INPUT dt
1380 runs=(th-t1)/tint+1

```

```

1390 GOTO 1500
1400 runs=1
1410 GOTO 1500
1499 !
1500 ! Set up storage for the experiment.
1510 NR=6
1520 IF runtyp$="ntemp" THEN NR=NR+NT+1
1530 IF runtyp$="trange" THEN NR=NR+1
1540 LL$=L$&".TX"
1542 MASS STORAGE IS "/vol1"
1545 ON ERROR GOTO 2000
1550 CREATE LL$,NR,256
1560 ASSIGN# 1 TO LL$
1565 PRINT# 1 ; runs
1570 PRINT# 1 ; title$
1580 PRINT# 1 ; subtitle$
1590 PRINT# 1 ; runtyp$
1600 PRINT# 1 ; L$
1610 PRINT# 1 ; tint,deti,dlay
1620 PRINT# 1 ; x12,x23
1630 IF runtyp$="trange" THEN PRINT# 1 ; t1,th,dt
1640 IF runtyp$="ntemp" THEN 1650 ELSE 1700
1650 PRINT# 1 ; NT
1660 FOR jt=1 TO NT @ PRINT# 1 ; tc(jt) @ NEXT jt
1700 ASSIGN# 1 TO * @ ! Close the file
1705 MASS STORAGE IS "/mstr/basfo"
1710 ASSIGN# 1 TO "name"
1720 PRINT# 1 ; L$
1730 ASSIGN# 1 TO *
1800 CLEAR @ DISP USING 1810
1810 IMAGE " TEMP " ,3X," DFSVTY ",3X," ETA ",3X,"STD DEV"
1900 CHAIN runtyp$
2000 OFF ERROR
2010 IF ERRN=63 THEN 2020 ELSE 2200
2020 ASSIGN# 1 TO LL$
2030 READ# 1 ; oldruns
2040 READ# 1 ; oldtitle$
2050 ASSIGN# 1 TO *
2060 DISP " File: ";L$
2070 DISP title$
2080 DISP oldruns
2090 DISP "Increment number of runs? (y/n)" @ INPUT qm$
2100 IF qm$="y" THEN 2110 ELSE 2200
2110 runs=runs+oldruns
2120 IF title$=oldtitle$ THEN 1560
2200 ERRM
2210 IF ERRN<>63 THEN 2300
2220 DISP "Old title: ";oldtitle$
2230 DISP "New title: ";title$
2240 DISP "Use old title? (y/n)" @ INPUT qm$
2250 IF qm$="y" THEN title$=oldtitle$ ELSE 2300
2260 GOTO 1560
2300 DISP "This action will DESTROY data."

```

```

2310 DISP "Execution of this program is terminated."
2320 BEEP @ GOTO 2320

```

```

10 !AUTO
20 COM t1(200),t2(200),t3(200),dtdt(200),d2tdx(200),tdfs(200)
30 COM eta(200),xs(200),ys(200),tc(50),tbar(200)
40 COM runum,jr,tint,dti,dlay,x12,x23,t1,th,dt,NT,runtyp,etabar,sd(200)
50 COM tau
90 ASSIGN 7 TO "hpib"
100 ASSIGN# 1 TO "name"
110 READ# 1 ; L$
120 ASSIGN# 1 TO *
121 LL$=L$&".TX" @ MASS STORAGE IS "/vol1"
122 ASSIGN# 1 TO LL$
123 READ# 1 ; runs
124 READ# 1 ; title$
125 ASSIGN# 1 TO *
130 DISP "SAMPLE # ";title$
140 DISP "STORED AS ";L$
150 DISP "SET TIME IN MINUTES BETWEEN OBSERVATIONS"
160 INPUT TOBS
170 TOBS=TOBS*60000
175 MASS STORAGE IS "/mstr/basfo"
180 FINDPROG "TAKEDATA"
190 FINDPROG "TDREDUCE"
200 FINDPROG "TDSTORE"
210 ASSIGN 7 TO "hpib"
220 MASS STORAGE IS "/vol1"
230 CALL "TAKEDATA"
235 runum=runum+1
240 CALL "TDREDUCE"
250 CALL "TDSTORE" (L$)
255 ON TIMER# 1,TOBS GOTO 230
260 OFF KEY# @ ON KEY# 1,"PARMS" GOTO 300
270 ON KEY# 16,"STOP" GOTO 880
290 GOTO 290
300 OFF KEY#
310 ON KEY# 1,"PLOT" GOTO 410
320 ON KEY# 2,"TOBS" GOTO 710
330 ON KEY# 3,"TINT" GOSUB 750
340 ON KEY# 4,"DETI" GOSUB 790
350 ON KEY# 5,"DELAY" GOSUB 840
360 ON KEY# 8,"RESUME" GOTO 1800
370 GOTO 370
410 rn$=VAL$(runum) @ LL$=L$&". "&rn$
420 ! Set plotting options
425 tbar=tbar(runum) @ tdfs=tdfs(runum) @ OFF KEY#
430 LT$=L$&".TX"
440 ASSIGN# 1 TO LT$
450 READ# 1 ; runs

```

```

460 READ# 1 ; title$
470 ASSIGN# 1 TO *
480 ON KEY# 1,"TMP/TIM" GOTO 570
490 ON KEY# 2,"DERIVS" GOTO 610
500 ON KEY# 8,"RETURN" GOTO 300
510 KEY LABEL
520 CLEAR @ DISP " SELECT THE TYPE OF PLOT USING THE FUNCTION KEYS"
530 DISP "      <f1> Temperatures vs. time  "
540 DISP "      <f2> dT/dt vs. d2T/dx2  "
550 DISP " " @ DISP "      <f8> Return to main menu."
560 GOTO 560
570 ymax=INT(t1(jr)) @ xmax=deti/1000 @ fl=1
580 IF ymax=0 THEN ymax=1
590 xlbl$="TIME (sec)" @ ylbl$="TEMP. CHANGE (C)"
600 GOTO 900
610 ymax=MAXAB(ys) @ xmax=MAXAB(xs) @ xmax=INT(xmax)+1 @ fl=2
620 IF ymax<1 THEN 630 ELSE 680
630 za=1
640 za=10*za
650 IF za*ymax<1 THEN 640
660 ymax=INT(za*ymax+1)/za
670 GOTO 690
680 ymax=INT(ymax+1)
690 xlbl$="d2T/dx2" @ ylbl$="dT/dt"
700 GOTO 900
710 DISP "SET TIME IN MINUTES BETWEEN OBSERVATIONS"
720 INPUT TOBS
730 TOBS=TOBS*60000
740 OFF KEY# @ GOTO 255
750 DISP "SET TINT"
760 DISP "OLD TINT = ";tint
770 INPUT tint
780 RETURN
790 DISP " SET DETI -- TIME FOR EXPERIMENT"
800 DISP "OLD DETI = ";deti
810 INPUT deti
820 RETURN
830 END
840 DISP "SET DELAY"
850 DISP " OLD DELAY = ";dlay
860 INPUT dlay
870 RETURN
880 MASS STORAGE IS "/mstr/basfo"
890 END
900 ! plotting routine
910 GCLEAR @ DEG @ CSIZE 4,0.6
920 LOCATE 0,200,0,100
930 SCALE (-0.5)*xmax,1.05*xmax,(-0.2)*ymax,1.15*ymax
940 CLIP 0,xmax,0,ymax
950 AXES xmax/5,ymax/5,0,0 @ AXES xmax/5,ymax/5,xmax,ymax
960 LDIR 0 @ LOR 2
970 y=(-0.05)*ymax
980 FOR x=0 TO xmax STEP xmax/5

```

```

990 MOVE x,y
1000 LABEL x
1010 NEXT x
1020 MOVE xmax/2,(-0.12)*ymax
1030 LABEL x1b1$
1040 x=0.32*xmax @ LORG 8
1050 FOR y=0 TO ymax STEP ymax/5
1060 MOVE x,y
1070 LABEL y
1080 NEXT y
1090 LDIR 90 @ LORG 5
1100 MOVE (-0.1)*xmax,0.6*ymax
1110 LABEL y1b1$
1120 LDIR 0 @ LORG 2
1130 MOVE 0.05*xmax,1.04*ymax
1140 LABEL title$
1150 MOVE 0.05*xmax,0.9*ymax
1160 LABEL "T = "
1170 MOVE 0.1*xmax,0.9*ymax
1180 tbar=INT(100*tbar)/100
1190 LABEL tbar
1200 IF f1=1 THEN 1230
1210 GOTO 1590
1220 ! Plot the temperature vs. time data
1230 FOR j=1 TO jr
1240 x=j*tint*0.001
1250 y=t1(j)
1260 MOVE x,y @ GOSUB 1670
1270 y=t2(j)
1280 MOVE x,y @ GOSUB 1700
1290 y=t3(j)
1300 MOVE x,y @ GOSUB 1670 @ GOSUB 1700
1310 NEXT j
1320 ! Add additional data to the plot
1330 LDIR 0 @ LORG 2 @ CSIZE 4,0.6
1340 MOVE (-0.4)*xmax,1.04*ymax
1350 LABEL "DATA"
1360 CSIZE 3,0.6
1370 MOVE (-0.5)*xmax,0.9*ymax @ LABEL "DELAY = "
1380 MOVE (-0.4)*xmax,0.9*ymax @ LABEL dlay
1390 MOVE (-0.5)*xmax,0.8*ymax @ LABEL "T-INT = "
1400 MOVE (-0.4)*xmax,0.8*ymax @ LABEL tint
1410 MOVE (-0.5)*xmax,0.7*ymax @ LABEL "TDFSUTY = "
1420 tdfs=INT(tdfs*100000)/100000
1430 MOVE (-0.38)*xmax,0.7*ymax @ LABEL tdfs
1440 MOVE (-0.5)*xmax,0.6*ymax @ LABEL "L$ = "
1450 MOVE (-0.42)*xmax,0.6*ymax @ LABEL LL$
1460 MOVE (-0.5)*xmax,0.5*ymax @ LABEL "x12 ="
1470 MOVE (-0.4)*xmax,0.5*ymax @ LABEL x12
1480 MOVE (-0.5)*xmax,0.4*ymax @ LABEL "x23 ="
1490 MOVE (-0.4)*xmax,0.4*ymax @ LABEL x23
1500 MOVE (-0.5)*xmax,0.3*ymax @ LABEL "TIME CONST. ="
1510 MOVE (-0.3)*xmax,0.3*ymax @ LABEL tau

```

```

1520 MOVE (-0.5)*xmax,0.2*ymax @ LABEL "STD. DEV. ="
1530 sd=INT(sd(runum)*1000000)/1000000
1540 MOVE (-0.3)*xmax,0.2*ymax @ LABEL sd
1550 MOVE (-0.5)*xmax,0.1*ymax @ LABEL "ETA ="
1560 etabar=INT(etabar*100000)/100000
1570 MOVE (-0.4)*xmax,0.1*ymax @ LABEL etabar
1580 CLEAR @ GOTO 420
1590 ! dtdt vs d2tdx2 plots
1600 FOR jp=2 TO jr-1
1610 MOVE xs(jp),ys(jp) @ GOSUB 1670
1620 NEXT jp
1630 ! Draw the regression line
1640 MOVE 0,0 @ y=tdfs*xmax
1650 LINE TYPE 1 @ DRAW xmax,y
1660 GOTO 1330
1670 ! plus symbol
1680 SETGU @ IDRAW 1,0 @ IDRAW -2,0 @ IDRAW 1,0 @ IDRAW 0,1 @ IDRAW 0,-2
@ IDRAW 0,1
1690 SETUU @ RETURN
1700 ! x symbol
1710 SETGU @ IDRAW 1,1 @ IDRAW -2,-2 @ IDRAW 1,1 @ IDRAW -1,1 @ IDRAW 2,-2
@ IDRAW -1,1
1720 SETUU @ RETURN
1800 !UPDATE THE DISPLAY
1810 CLEAR @ DISP "SAMPLE # ";title$
1820 DISP "STORED AS ";L$
1830 DISP "TIME BETWEEN MEASUREMENTS ";TOBS/60000
1840 DISP USING 1850
1850 IMAGE " TEMP ",3X," DFSVTY ",3X," ETA ",3X,"STD DEV"
1860 FOR JU=1 TO runum
1870 DISP USING 1890 ; tbar(JU);tdfs(JU);eta(JU);sd(JU)
1880 NEXT JU
1890 IMAGE DDD.DD,3(3X,DD.SD)
1900 GOTO 260

```



```

10 SUB "TAKEDATA"
30 COM t1(200),t2(200),t3(200),dtdt(200),d2tdx(200),tdfs(200)
40 COM eta(200),xs(200),yx(200),tc(50),tbar(200)
50 COM runum,jr,tint,dti,dlay,x12,x23,t1,th,dt,NT,runtyp,etabar,sd(200)
60 COM tau
70 GOTO 150
80 GOTO 80
90 TRIGGER vm1,vm2,vm3 @ jr=jr+1
100 ENTER vm1 ; t1(jr) @ ENTER vm2 ; t2(jr) @ ENTER vm3 ; t3(jr)
110 GOTO 110
120 OFF TIMER# 3 @ GOTO 310
130 OFF TIMER# 2 @ OFF TIMER# 1
140 OUTPUT dac ; "opn 0" @ GOTO 340
150 ! Set up instruments
170 dac=709 @ vm1=723 @ vm2=724 @ vm3=725 @ !hpib addresses
180 ! set up voltmeters
190 FOR ji=0 TO 2 @ vm=vm1+ji @ OUTPUT vm ; "F1R-2T4Z0N5" @ NEXT ji
200 OUTPUT dac ; "opn 0 "
210 ! get the temperature baseline
220 TRIGGER vm1,vm2,vm3
230 ENTER vm1 ; t1(0)
240 ENTER vm2 ; t2(0)
250 ENTER vm3 ; t3(0)
260 jr=0
270 OUTPUT dac ; "cls 0"
280 IF dlay<10 THEN 310
290 ON TIMER# 3,dlay GOTO 120
300 GOTO 300
310 ON TIMER# 1,dti GOTO 130
320 ON TIMER# 2,tint GOTO 90
330 GOTO 80
340 FOR ji=0 TO 2 @ vm=vm1+ji @ OUTPUT vm ; "T1" @ NEXT ji
360 SUBEND

```

```

10 SUB "TDREDUCE"
20 ! tdreduce
30 COM t1(200),t2(200),t3(200),dtdt(200),d2tdx(200),tdfs(200)
40 COM eta(200),xs(200),ys(200),tc(50),tbar(200)
50 COM runum,jr,tint,dti,dlay,x12,x23,t1,th,dt,NT,runtyp,etabar,sd(200)
60 COM tau
70 xbar=0.5*(x12+x23)
80 at=25.33 @ bt=-0.352 @ ct=0.032
90 ! Convert voltages to temperatures
100 FOR j=0 TO jr
110 tt=t1(j)*1000 @ t1(j)=tt*(at+tt*(bt+tt*ct))
120 tt=t2(j)*1000 @ t2(j)=tt*(at+tt*(bt+tt*ct))
130 tt=t3(j)*1000 @ t3(j)=tt*(at+tt*(bt+tt*ct))
140 NEXT j
150 ! Calculate the time derivatives of t2
160 n=8
170 sj=0 @ sj2=0 @ st=0 @ sjt=0

```

```

180 FOR j=1 TO 2*n+1
190 sj=sj+j @ sj2=sj2+j*j
200 st=st+t2(j) @ sjt=sjt+j*t2(j)
210 NEXT j
220 dtdt(n+1)=1000*((2*n+1)*sjt-sj*st)/(tint*((2*n+1)*sj2-sj*sj))
230 FOR j=n+2 TO jr-n
240 sj=sj+n*n+1 @ sj2=sj2-(j-n-1)*(j-n-1)+(j+n)*(j+n)
250 st=st-t2(j-n-1)+t2(j+n) @ sjt=sjt-(j-n-1)*t2(j-n-1)+(j+n)*t2(j+n)
260 dtdt(j)=1000*((2*n+1)*sjt-sj*st)/(tint*((2*n+1)*sj2-sj*sj))
270 NEXT j
280 ! Get the delta t's and the laplacian
290 FOR j=1 TO jr
300 t1(j)=t1(j)-t1(0) @ t2(j)=t2(j)-t2(0) @ t3(j)=t3(j)-t3(0)
310 d2tdx(j)=((t3(j)-t2(j))/x23-(t2(j)-t1(j))/x12)/xbar
320 NEXT j
330 ! Get the thermal diffusivity by least squares
340 sx=0 @ sx2=0 @ sy=0 @ sxy=0 @ st=0 @ set=0 @ sy2=0
350 FOR j=n+1 TO jr-n
360 x=(d2tdx(j-1)+d2tdx(j)+d2tdx(j+1))/3
370 xs(j)=x
380 y=dtdt(j)
390 ys(j)=y
400 sxy=sxy+x*y
410 sx2=sx2+x*x
420 sy2=sy2+y*y
430 st=st+t2(j)
440 eta(j)=y/x
450 set=set+y/x
460 NEXT j
470 tdfs(runum)=sxy/sx2
480 tbar(runum)=st/(jr-2*n)+t2(0)
490 etabar=set/(jr-2*n)
500 sd=SQR((sy2-sxy*sxy/sx2)/(jr-2))/x @ sd(runum)=sd
510 DISP USING 520 ; tbar(runum);tdfs(runum);etabar;sd(runum)
520 IMAGE DDD.DD,3(3X,DD,SD)
530 eta(runum)=etabar
540 SUBEND

```

```

10 SUB "TDSTORE" (L$)
20 ! tdstore
30 COM t1(200),t2(200),t3(200),dtdt(200),d2tdx(200),tdfs(200)
40 COM eta(200),xs(200),ys(200),tc(50),tbar(200)
50 COM runum,jr,tint,dti,dlay,x12,x23,t1,th,dt,NT,runtyp,etabar,sd(200)
60 COM tau
70 sd=sd(runum)
100 rn$=VAL$(runum)
110 LL$=L$&"."&rn$
120 CREATE LL$,jr+8,40
130 ASSIGN# 1 TO LL$
140 PRINT# 1 ; LL$

```

```

150 PRINT# 1 ; tbar(runum),tdfs(runum),etabar,sd
160 PRINT# 1 ; x12,x23
170 PRINT# 1 ; tint,deti,dlay,tau
180 PRINT# 1 ; jr
190 FOR js=0 TO jr
200 PRINT# 1 ; t1(js),t2(js),t3(js),xs(js),ys(js)
210 NEXT js
220 ASSIGN# 1 TO *
225 GOTO 260
260 SUBEND

```

```

10 ! tdplot
20 MASS STORAGE IS "/vol1"
999 CLEAR
1000 DISP " THIS PROGRAM READS THERMAL DIFFUSIVITY DATA FILES"
1001 DISP " AND MAKES PLOTS ON THE SCREEN"
1005 DIM t1(200),t2(200),t3(200),xs(200),ys(200),yx(200)
1006 DIM y1b1$(130)
1010 DISP " "
1020 DISP "The file names have the form FFFFFFFFFF.##"
1030 DISP " Enter FFFFFFFFFF" @ INPUT LL$
1031 LT$=LL$&".TX" @ ASSIGN# 1 TO LT$ @ READ# 1 ; runs
1032 READ# 1 ; title$
1033 ASSIGN# 1 TO *
1035 DISP "Enter ##" @ INPUT rn
1036 rn$=VAL$(rn)
1040 L$=LL$&". "&rn$
1050 ASSIGN# 1 TO L$
1160 READ# 1 ; L$
1170 READ# 1 ; tbar,tdfs,eta,sd
1180 READ# 1 ; x12,x23
1190 READ# 1 ; tint,deti,dlay,tau
1200 READ# 1 ; jr
1320 FOR j=0 TO jr
1330 READ# 1 ; t1(j),t2(j),t3(j),xs(j),ys(j)
1340 NEXT j
1350 ! Set plotting options
1360 ON KEY# 1,"TMP/TIM" GOTO 1450
1370 ON KEY# 2,"DERIVS" GOTO 1500
1375 ON KEY# 5,"NEW FILE" GOTO 1530
1376 ON KEY# 8,"QUIT" GOTO 1700
1380 KEY LABEL
1390 CLEAR @ DISP " SELECT THE TYPE OF PLOT USING THE FUNCTION KEYS"
1400 DISP "      <f1> Temperatures vs. time "
1410 DISP "      <f2> dT/dt vs. d2T/dx2 "
1420 DISP " " @ DISP "      <f5> Change file"
1430 DISP " " @ DISP "      <f8> Quit"
1440 GOTO 1440
1450 ymax=INT(t1(jr)) @ xmax=deti/1000 @ fl=1
1455 IF ymax=0 THEN ymax=1
1460 x1b1$="TIME (sec)" @ y1b1$="TEMP. CHANGE (C)"

```

```

1470 GOTO 2000
1500 ymax=MAXAB(ys) @ xmax=MAXAB(xs) @ xmax=INT(xmax)+1 @ fl=2
1510 IF ymax<1 THEN 1512 ELSE 1518
1512 za=1
1513 za=10*za
1514 IF za*ymax<1 THEN 1513
1515 ymax=INT(za*ymax+1)/za
1516 GOTO 1519
1518 ymax=INT(ymax+1)
1519 x1b1$="d2T/dx2" @ y1b1$="dT/dt"
1520 GOTO 2000
1530 OFF KEY#
1540 DISP "The file names have the form FFFFFFFFFF.##"
1550 ON KEY# 1,"FFFFF" GOTO 1590
1560 ON KEY# 2,"##" GOTO 1610
1570 KEY LABEL
1580 GOTO 1580
1590 OFF KEY#
1600 GOTO 1030
1610 OFF KEY#
1620 GOTO 1035
1700 END
2000 ! plotting routine
2010 GCLEAR @ DEG @ CSIZE 4,0.6
2020 LOCATE 0,200,0,100
2030 SCALE (-0.5)*xmax,1.05*xmax,(-0.2)*ymax,1.15*ymax
2050 CLIP 0,xmax,0,ymax
2060 AXES xmax/5,ymax/5,0,0 @ AXES xmax/5,ymax/5,xmax,ymax
2070 LDIR 0 @ LORG 2
2080 y=(-0.05)*ymax
2090 FOR x=0 TO xmax STEP xmax/5
2100 MOVE x,y
2110 LABEL x
2120 NEXT x
2130 MOVE xmax/2,(-0.12)*ymax
2140 LABEL x1b1$
2150 x=0.32*xmax @ LORG 8
2160 FOR y=0 TO ymax STEP ymax/5
2170 MOVE x,y
2180 LABEL y
2190 NEXT y
2200 LDIR 90 @ LORG 5
2210 MOVE (-0.1)*xmax,0.6*ymax
2220 LABEL y1b1$
2230 LDIR 0 @ LORG 2
2240 MOVE 0.05*xmax,1.04*ymax
2250 LABEL title$
2260 MOVE 0.05*xmax,0.9*ymax
2270 LABEL "T = "
2280 MOVE 0.1*xmax,0.9*ymax
2285 tbar=INT(100*tbar)/100
2290 LABEL tbar
2900 IF fl=1 THEN 3000

```

```

2910 GOTO 3500
2999 ! Plot the temperature vs. time data
3000 FOR j=1 TO jr
3010 x=j*tint*0.001
3020 y=t1(j)
3030 MOVE x,y @ GOSUB 4500
3040 y=t2(j)
3050 MOVE x,y @ GOSUB 4530
3060 y=t3(j)
3070 MOVE x,y @ GOSUB 4500 @ GOSUB 4530
3080 NEXT j
3090 ! Add additional data to the plot
3100 LDIR 0 @ LONG 2 @ CSIZE 4,0.6
3110 MOVE (-0.4)*xmax,1.04*ymax
3120 LABEL "DATA"
3130 CSIZE 3,0.6
3140 MOVE (-0.5)*xmax,0.9*ymax @ LABEL "DELAY = "
3150 MOVE (-0.4)*xmax,0.9*ymax @ LABEL dlay
3160 MOVE (-0.5)*xmax,0.8*ymax @ LABEL "T-INT = "
3170 MOVE (-0.4)*xmax,0.8*ymax @ LABEL tint
3180 MOVE (-0.5)*xmax,0.7*ymax @ LABEL "TDFSUTY = "
3185 tdfs=INT(tdfs*100000)/100000
3190 MOVE (-0.38)*xmax,0.7*ymax @ LABEL tdfs
3200 MOVE (-0.5)*xmax,0.6*ymax @ LABEL "L$ = "
3210 MOVE (-0.42)*xmax,0.6*ymax @ LABEL L$
3220 MOVE (-0.5)*xmax,0.5*ymax @ LABEL "x12 = "
3230 MOVE (-0.4)*xmax,0.5*ymax @ LABEL x12
3240 MOVE (-0.5)*xmax,0.4*ymax @ LABEL "x23 = "
3250 MOVE (-0.4)*xmax,0.4*ymax @ LABEL x23
3260 MOVE (-0.5)*xmax,0.3*ymax @ LABEL "TIME CONST. ="
3270 MOVE (-0.3)*xmax,0.3*ymax @ LABEL tau
3280 MOVE (-0.5)*xmax,0.2*ymax @ LABEL "STD. DEV. ="
3285 sd=INT(sd*1000000)/1000000
3290 MOVE (-0.3)*xmax,0.2*ymax @ LABEL sd
3300 MOVE (-0.5)*xmax,0.1*ymax @ LABEL "ETA ="
3305 eta=INT(eta*100000)/100000
3310 MOVE (-0.4)*xmax,0.1*ymax @ LABEL eta
3390 CLEAR @ GOTO 1350
3500 ! dtdt vs d2tdx2 plots
3510 FOR jp=2 TO jr-1
3520 MOVE xs(jp),ys(jp) @ GOSUB 4500
3530 NEXT jp
3540 ! Draw the regression line
3550 MOVE 0,0 @ y=tdfs*xmax
3560 LINE TYPE 1 @ DRAW xmax,y
3570 GOTO 3100
4500 ! plus symbol
4510 SETGU @ IDRAW 1,0 @ IDRAW -2,0 @ IDRAW 1,0 @ IDRAW 0,1 @ IDRAW 0,-2
@ IDRAW 0,1
4520 SETUU @ RETURN
4530 ! x symbol
4540 SETGU @ IDRAW 1,1 @ IDRAW -2,-2 @ IDRAW 1,1 @ IDRAW -1,1 @ IDRAW 2,-2
@ IDRAW -1,1
4550 SETUU @ RETURN

```

VITA

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Master of Science

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